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About the possibility of creation of sealed strong structures of rocket and space equipment FDM printing methods

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Abstract.The work shows the possibility of manufacturing products for rocket and space technology using the additive FDM-printing technology. The object of research is the nozzle plugs of the "membrane" type. Taking into account the specific-strength properties of the product during its operation during operation, as well as the features of the FDM-process, the design was optimized, the regularities of the formation of its properties were established. An impregnation technology has been developed to seal the product. The equipment was designed and pneumatic tests were carried out. The properties of materials were investigated taking into account their guaranteed shelf life for 12 years of operation under accelerated climatic tests. It is shown that the production of products by FDM-printing methods is promising and expedient, since the properties being formed are predictable, achievable and stable.
<u>*Keywords:*</u> *nozzle plug, additive technologies, 3D printing, strength calculations, pneumatic tests*

Non-metallic materials used in the rocket and space industry is a compromise between low weight, high physical and mechanical properties, and safety. The operation of lightweight structures made of these materials must meet the following parameters [1–3]:
- minimum weight;
- maximum rigidity and strength of parts;
- maximum service life of structures under operating conditions;
- high reliability.

Recently, in addition to increasing the specific-strength and resource properties of materials and structures, the issue of increasing costs for the manufacture and development of products in a single production is acutely felt. The introduction of 3D printing technology (in particular, FDM processes), which makes it possible to manufacture products of any shape and complexity in one technological transition, without additional processing, is seen as an alternative to expensive shaping tooling for the manufacture of complex-shaped products with subsequent machining. Despite the obvious advantages of the technology, the use of such materials in the structures of rocket and space technology (RST) has not been introduced due to a number of features, in particular, limited strength properties, the resulting anisotropy determined by the printing (layout) conditions, the permeability of the resulting products to gases, and in some cases, highly fluid liquids, low temperature resistance, and others.

The aim of the work is to assess the possibility of obtaining sealed structures for rocket and spacecraft by the FDM process [4].

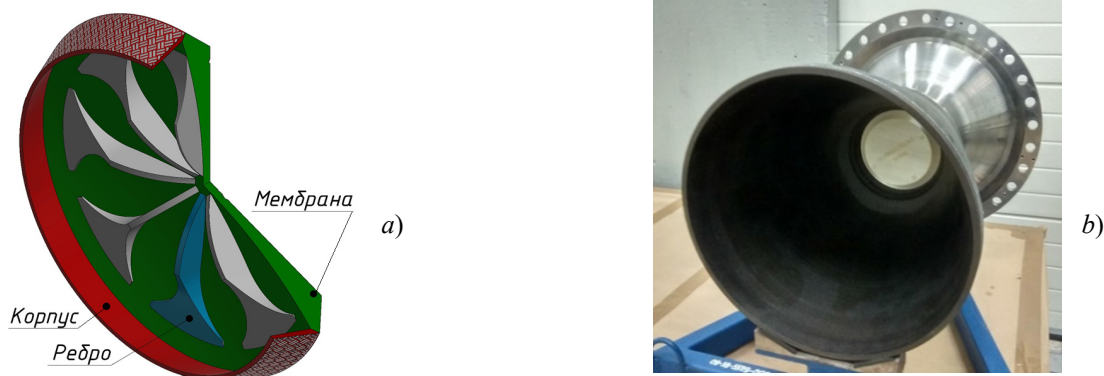As an object of analysis, a nozzle plug installed in the nozzle of a rocket engine was selected, Fig. 1.

Fig. 1. Nozzle plug (*a*) and its installation into the nozzle of the main engine (*b*)

As usually, aluminum alloys are used as the nozzle plug material. The plug developed at the Yuzhnoye Design Bureau is completely made of thermoplastic and does not have metal inserts, while the use of such materials reduces its weight, which also minimizes the size of the danger zone for service personnel when it is triggered. In addition, hitting possible obstacles, such plugs are destroyed, while reducing the likelihood of damage to structural elements and personnel during a ricochet. The developed nozzle plug is one integral part, which can be conditionally divided into 3 parts: body, fin and membrane. Each of them has its own functional purpose:

- opening zone – the joint between the body and the membrane, the strength of which should be minimal in the structure and at the same time ensure the operation of the plug in the range of gas-dynamic pressure $(0,6 \pm 0,3)$ MPa;

- the body is made conical with a ribbed outer surface and is designed for tight and strong gluing directly to the nozzle material, the strength of the gluing, taking into account its area, should be higher than the strength of the opening zone;

- the membrane is made hermetic due to material impregnation and is designed to protect the inner space of the nozzle from external factors;

- stiffening ribs are designed to strengthen the membrane in such a way that the destruction of the nozzle plug is carried out not along the membrane itself, but along the opening zone.

The prototypes of the nozzle plug were presented in the following versions, Fig. 2.

The original version had a 3 mm thick membrane with an annular groove 1 mm deep to weaken the section (the supposed fracture site), 12 ribs converging in the center to concentrate the stresses acting on the membrane. The outer area of the body for the bonding is 224.3 cm², weight 212 g. The version of the nozzle plug, having a membrane thickness of 4-11 mm, had 8 ribs of a more complex configuration for even distribution of stresses acting on the membrane. The outer area of the body for the gluing has decreased to 205.1 cm² due to the decrease in the body height. Mass due to massive ribs increased to 298 g. The final version of the nozzle plug had a smoothly varying membrane thickness from 4 mm to 14 mm, 8 ribs for uniform distribution of stresses acting on the membrane. The outer area of the body for the gluing has decreased to 108.8 cm² due to the decrease in the body height. Due to the increase in membrane thickness, the mass increased slightly, up to 317 g.

Preliminary analysis of designs of nozzle plugs of variants performed using CAD software Autodesk Inventor Professional 2018. For each analysis the following conditions are accepted: the material of the part is isotropic; the load is applied to the surface from the side of the working cavity;

the outer surface of the body is rigidly fixed and has no movement; plastic deformations begin at stresses above 33 MPa; destruction begins at internal stresses over 42 MPa.

For option No. 1, the expected fracture pressure was 0.4 MPa; the maximum value of stresses is in the annular groove at the point of transition of the membrane into the body; the place of the beginning of the destruction is in the annular groove; stress concentration - at the center of the ribs; the maximum calculated displacement of the center of the membrane at a pressure of 0.15 MPa - more than 1.0 mm, at a pressure of 0.3 MPa - more than 3.0 mm. This option has a low response pressure and high displacement rates, which does not exclude the possibility of damage to the impregnation material, which ensures the tightness of the part, in the process of repeated loading with a certain cyclicity.

Option No. 2 (Fig. 2, *b*) turned out to be more successful: the expected fracture pressure is 1.05 MPa; the maximum value of stresses is at the point of transition of the membrane into the body; the place of the beginning of destruction - along the line of transition of the membrane into the body; stress concentration - in places where ribs are present on the inner side of the body; the maximum calculated displacement of the center of the membrane at a pressure of 0.15 MPa is about 0.55 mm, at pressure of 0.3 MPa - more than 1.1 mm.
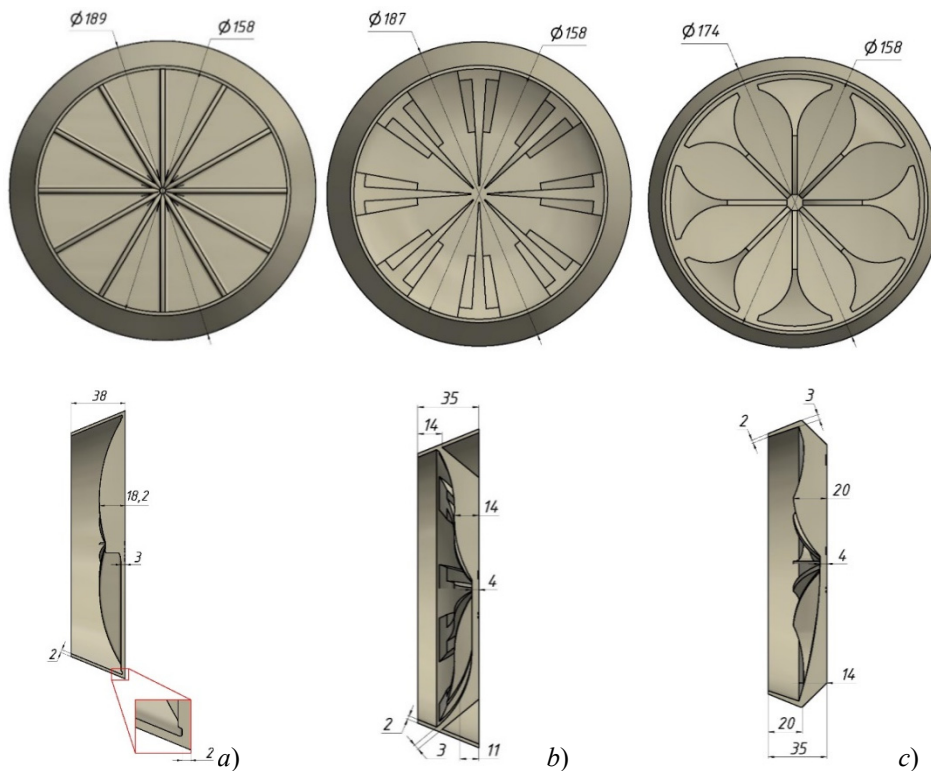

Fig. 2. Options of the nozzle plug: No.1; No.2; No.3

This option has a high response pressure, exceeding the working range requirement, but low displacement rates indicate a high structural rigidity. In the center, on the reverse side of the membrane, there is a stress concentration, while on the side of the working cavity, there is no stress concentration. These stresses are not critical and indicate the presence of displacements in the central region of the membrane.

The last option (Fig. 2, *c*) showed the following results: fracture pressure – 0.7 MPa; the maximum value of stresses is along the transition of the membrane to the body; the place of the beginning of destruction – at the point of transition of the membrane into the body; stress

concentration - from the side of the working cavity along the circumference of the membrane transition into the body; the maximum calculated displacement of the center of the membrane at a pressure of 0.15 MPa - no more than 0.62 mm, at a pressure of 0.3 MPa - about 1.25 mm. This option has an optimal response pressure within the operating range. A slight increase in the movement of the membrane in comparison with option No. 2 is not critical. The stress concentration is dispersed along the edges of the membrane, which indicates the optimal shape of the ribs as elements of the load distribution acting on the membrane.

Thus, based on the strength calculations carried out in the CAD software Autodesk Inventor Professional 2018, the nozzle plug option No. 3 is the closest to the functional requirements. It is this variant of the nozzle plug that is most expedient to choose as the main one. For it, additional strength calculations were carried out in the software of the Ansys Static Structural package to refine and compare the results. Strength calculation is carried out in order to determine the displacements when checking the plug for tightness, as well as to determine the response pressure of the plug.

Mechanical tests and subsequent fracture analysis of prototype samples showed the following. For sample No. 1, the destruction occurred partially not in the calculated place and between the layers of the print. This can be explained by the fact that the anisotropy of properties was not taken into account when laying out the layers. The destruction of the nozzle plug No. 2 occurred almost at the calculated location, but at the same time, a part of the body with a height of ≈25 mm was also torn off. And only sample No. 3 showed the convergence of the calculated and experimental results: during the tests, the destruction of the nozzle plug occurred in the calculated place.

Smooth pressure loading of the test specimens showed quite interesting results. Due to the permeability of the material, the pressure was partially vented, and at low air inflows on the experimental setup in Fig. 3, the destruction of the sample practically did not occur [5].

This required additional impregnation of the outer layers of the finished product with special adhesives, as a result of which it was possible to obtain a sufficiently tight surface layer shown in Fig. 4. To carry out tests on the study of the permeability of the plugs, special equipment was designed and manufactured. The test method consists in creating in the inner part of the plug a vacuum of air with a value of more than 100 Pa with fixing the decay of the vacuum for 15 minutes. The test results are considered satisfactory with no drop at all [6].
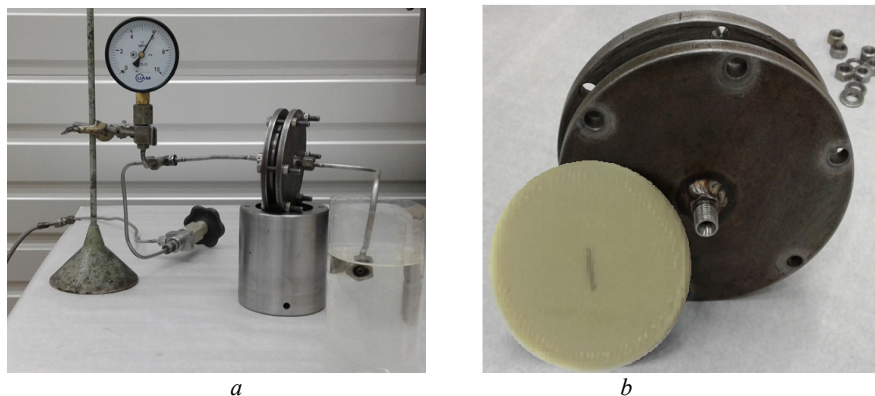

Fig. 3. Stand for testing for permeability (a) and an open fixture with an installed sample (b)

Penetration tests were carried out initially with plugs prior to impregnation. For the entire batch of nozzle plugs, a complete decay of vacuum discharge was recorded within 15–45 seconds after the valve was closed. During tests, 20 out of 24 plugs after impregnation confirmed their impermeability, for 4 (17% of the batch) plugs a decrease in vacuum discharge was recorded, while the drop was much slower than that of plugs before impregnation. The time to complete decline was 5–7 minutes. To analyze the reasons for the permeability of the nozzle plug material, a comparison was made of

the glue deposition by weighing the parts in different states, as a result of which it was concluded that all plugs in the batch, including the permeable ones, had the same deposition within the total spread (the average plug mass before impregnation was 297.70 grams, 301.03 grams after impregnation). The caps were found to be permeable due to individual permeable pores that were not impregnated after the first application cycle. For these plugs, a second impregnation was carried out with an increase in the exposure time during the application of glue to 10 minutes and a cyclic application of glue was introduced. After re-impregnation, the parts proved to be impermeable when tested again. Subsequently, for the second and third batch of nozzle plugs in the amount of 24 pieces, each modified technology made it possible to obtain impermeable nozzle plugs in one impregnation step.
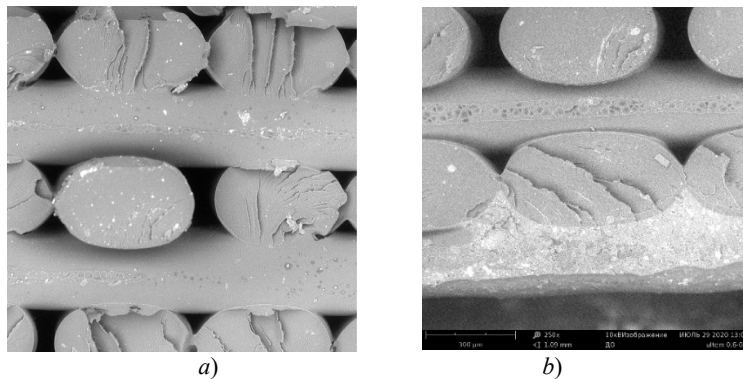

a)   *b*)

Fig. 4. microstructure of the sample after printing (a) and after impregnation with an adhesive composition (b)

To confirm the correctness of the design and technological solutions incorporated in the design of the nozzle plug, functional tests of operation on 7 plugs were carried out. All tests, regardless of the values, collapsed at a given place, namely in the zone of transition from the body to the nozzle membrane. The first plug was tested with a receiver pressure of 4.875 MPa (calculated). The results of pressure measurements in the cavity of the nozzle plug are shown in Fig. 5.
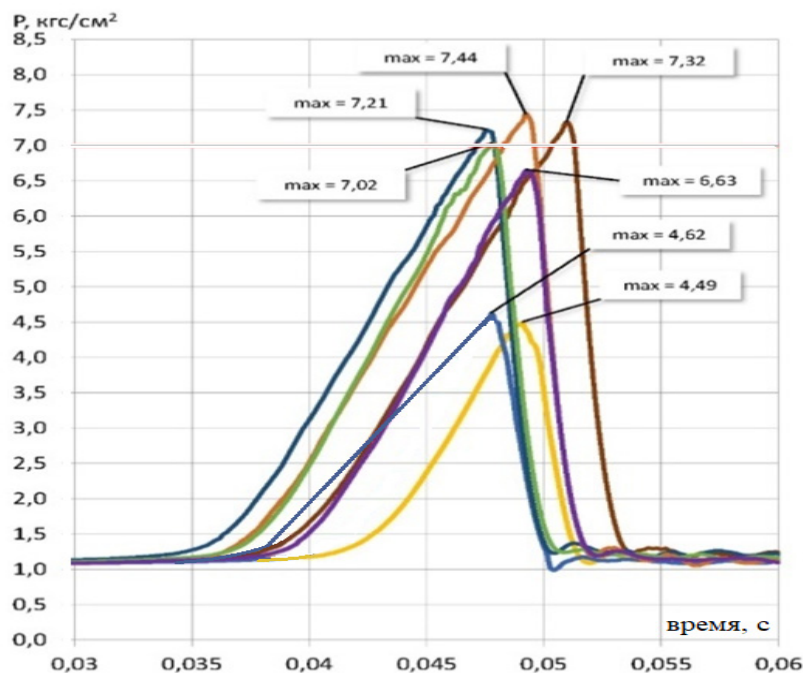

Fig. 5. Results of measurements of pressure in the cavity of the tooling during functional tests

For comparison, the figure shows the experimental dependence of the pressure in the combustion chamber on time. Obviously, the calculated pressure in the receiver is not enough to simulate the speed of the pneumatic pulse. For the second nozzle plug, the pressure in the receiver is 5.5 MPa. The measurement results are also shown in the figure. Considering the dependence of the rate of pressure build-up in the combustion chamber, in terms of its angle of inclination to the ordinate axis, to the ratio of the rate of pressure build-up in the cavity of the tooling during functional tests, it can be argued that the pressure value in the receiver cavity is correctly selected (5.0 ±0,5) MPa, flow sections of the equipment and length of pipelines to simulate the rate of pressure rise in the combustion chamber. The remaining 5 nozzle plugs were tested according to the mode of the second experiment.

As can be seen from the figure, all nozzle plugs during functional tests for actuation comply with the requirement for the actuation pressure range, which is (0,6 ± 0,3) MPa. As a result of the experiments, the response range was (0,6 ±0,15) MPa, which is 2 times less than the specified one. The average response pressure is 0,639 MPa. The average response time is 0.01 s, which in turn corresponds to the experimental pressure in the combustion chamber. Thus, it can be argued that the selected design and applied technologies meet the technical and functional requirements for the nozzle plug.

Thus, we can conclude that the use of ULTEM 9085 material impregnated with EPOTHERM-03t type A epoxy glue makes it possible to obtain high-quality critical elements of RST. The properties of materials were investigated taking into account their guaranteed shelf life for 12 years of operation under accelerated climatic tests. It is shown that the production of products by FDM-printing methods is promising and expedient, since the properties being formed are predictable, achievable and stable.

Про можливість створення герметичних міцних конструкцій ракетно-космічної техніки методами FDM друку

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Анотація. Робота доводить можливість виготовлення виробів ракетно-космічної техніки із застосуванням адитивної технології FDM-друку. Об'єктом досліджень є соплова заглушка типу «мембрана». З урахуванням питомо-міцнісних властивостей виробу при його функціонуванні в процесі експлуатації, а також особливостей FDM-процесу, проведена оптимізація конструкції, встановлені закономірності формування властивостей виробу. Розроблено технологію просочення для герметизації заглушки. Спроектовано оснащення і проведені пневматичні випробування готового виробу перед встановленням на штатне місце. Досліджено властивості матеріалів з урахуванням їх гарантійного терміну зберігання протягом 12 років експлуатації при прискорених кліматичних випробуваннях. Показано, що виконання виробів методами FDM-друку є перспективним і доцільним, оскільки властивості, що формуються, є прогнозованими, досяжними і стабільними.

<u>Ключові слова:</u> *соплова заглушка, адитивні технології, 3D-друк, розрахунки на міцність, пневматичні випробування*

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